



Optimized design of low-rise commercial buildings under various climates – Energy performance and passive cooling strategies

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ABSTRACT

The design of low-rise commercial building envelopes is mainly driven by functional large volumes, and low-cost and lightweight materials that often present weak thermal performances. Thermal and visual comfort is a key parameter for these buildings' purpose, but poor envelope designs have significant consequences on the high-energy demand for HVAC and artificial lighting systems. Considering the resources outside the building envelope for both cooling and heating seasons, this study aims to optimize the building design under various climates. Energy for ventilation, heating and lighting, and summer thermal discomfort are mitigated considering natural resources such as solar energy, low sky temperatures, ground inertia, and ambient air. For this specific building typology, main thermal fluxes are transmitted through large surfaces of soil (to the ground) and roof (to the environment). In the study, we found that summer thermal discomfort can be minimized, and near zero for some climates, without active cooling system. This objective is balanced by the energy demand objective; a multi-objective optimization using the NSGA-II algorithm gave optimal solutions according to local climate and global warming effects. This methodology and numerical results presented here can be helpful to design new commercial buildings and improve energy efficiency of existing ones. Most adapted set of design parameters for passive cooling solutions such as cool roofs and night natural ventilation are mapped for various climate, including climate change effects.

1. Introduction

The commercial sector presents a significant potential for energy saving and reduction of environmental impacts. Commercial buildings are actually responsible for 7% of the total world energy consumption [1]. This energy use is mostly due to heating and cooling systems with more than 60% of building consumption [2,3]. Commercial buildings represent more than 20 billion square meters in 2010 and their surface should increase fast in the future [4]. This surface would increase together with the population growth and higher living standards, and could be up to 80 billion square meters in 2050 [4]. The thermal performance improvement of commercial buildings, through their refurbishment or better designs of new constructions, can be promising in worldwide energy policies. Many studies focus on better design of air-conditioned building, but developing alternative cooling strategies without air-conditioning is a challenge for balancing increase of energy demand [4]. Actually, most buildings are still not air-conditioned either due to low standards of living or like in French climates where adequate design can be enough.

In order to minimize energy consumption of these buildings, we focus in this paper on heating, cooling, lighting and ventilation systems that ensure thermal and visual comfort. In this context, there are a wide variety of optimization parameters and strategies to tend toward low or near-zero energy buildings. For example, increasing roof albedo can significantly improve overall building performance except in some building typologies or for high insulation levels [5]. Unlike many published studies, we focus here on simultaneously optimal set of parameters for construction and ventilation control. Indeed, main progresses for NZEB should be obtained from a good combination of those key parameters [6]. A review of building thermal performance studies highlights various groups of key parameters such as building morphology and envelope's performance [7–10], building orientation, construction material [8,11,12], HVAC system operation and design [11,13,14]. Besides, the effect of climate change presents a significant impact on building energy consumption especially on heating and cooling system depending on climatic condition and building characteristics [4,15–19]. In order to predict the future climate, the HadCM3 is the most widely used model because of its high resolution

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[15–19]. Optimization process through all these parameter groups, even active systems, has to consider passive cooling or heating techniques, environmental resources and waste energy recovery. It has been demonstrated that passive cooling techniques such as cool roofs are highly dependent on building operation and occupant behavior [20].

In this paper, we considered the optimization of building envelope together with the control strategy for natural ventilation by taking into account the impact of climate change. However, some constraint parameters are fixed: occupancy patterns, ventilation modes, internal heat gains. Then, the real effectiveness of passive techniques is highly unpredictable, especially for free heating or cooling strategies, depending both on the climate and building environment, and on the latter building complex interrelationships of intrinsic parameters. The potential of cooling techniques for large flat roof, such as green or cool roofs, can be limited depending on the climate zone as demonstrated by several studies [21–23]. A suitable building design for one geographical location is not necessarily well suited to another location.

The objectives of this paper are (1) to develop an optimization tool using the NSGA-II algorithm [24] in order to evaluate the best configurations of low-rise building according to the climatic conditions and (2) to evaluate passive strategies' effectiveness regarding both energy performance and thermal comfort. In a first stage, we describe a generic low-rise commercial building together with the passive cooling strategies for this building typology. Then, we processed optimal solutions for different climates in term of energy consumption and summer comfort. We assessed sensitivities of key design parameters through the analysis of these commercial building optimal solutions. However, climate change can impact the performance of passive building design [25–27]. Then, climate change for the case of France is accounted for evaluating future optimal designs. The methodology and results of this study can be very useful for the architectures to design a passive building with similar characters in the future.

2. Description of the generic low-rise commercial building

The generic low-rise commercial building defined for this study is made of steel structure with a square floor surface of 36 m sides (Fig. 1). This simple building typology is common especially for commercial and industrial use due to various economic and practical advantages [28,29].

The building height is 6 m. The vertical exterior walls are well insulated and have a total thickness of 30.5 cm (1.3 cm of gypsum, 14 cm of glass wool, 15 cm of rock wool and an outer steel cladding of 2 mm). The thermal inertia of the building envelope is mainly due to the concrete slab (160 mm) which directly lies on sand. The terrace-flat roof has a thickness of 25.5 cm (24 cm rock wool, 2 mm outer steel cladding and 13 mm plasterboard) and is fitted with 31.36 m² of skylights (2.42% of the roof surface area). Vertical wall windows have a total surface of 30 m²; only the northern wall has no windows. Sizes and thermal properties of wall layers are detailed in Tables 1 and 2.

The commercial shelves stand on 30% of the floor surface area. These elements consist of cardboard (40%), liquids/oils (30%) metals (10%) and plastics (20%). The building air permeability level is

Table 1
Structure of the building envelope.

Wall	Material	Thickness (mm)	Thermal conductivity (W.m ⁻¹ .K ⁻¹)	Density (kg.m ⁻³)	Specific heat (J.kg ⁻¹ .K ⁻¹)
Vertical walls	Sheet steel	2	50	7800	419
	Stone wool	150	0.042	50	920
	Glass wool	140	0.038	50	840
	Plaster	13	0.25	825	801
Roof	Sheet steel	2	50	7800	419
	Glass wool	240	0.038	50	840
	Plaster	13	0.25	825	801
Slab	Concrete	160	2	2450	1000

Table 2
Windows properties.

Windows	Type	A _w (m ²)	U _w (W.m ⁻² .K ⁻¹)	F _w (–)	F _L (–)
Glass doors	Double glazing	6	2.89	0.789	0.747
Windows	Double glazing	24	2.89	0.789	0.747
Skylights	Double glazing	31.36	2.95	0.777	0.817

A_w: glazing surface area, U_w: heat transfer coefficient of the window, F_w: solar factor, F_L: light factor.

equivalent to 2 cm²/m² which is representative of a common steel construction building [30].

An occupation density of 11.6 m² per person is considered here [31]. The occupancy period is 07:00 a.m.–10:00 p.m. every day except on Sundays (empty building). A heating system is set to maintain the indoor temperature to a minimum of 19 °C when the building is occupied and 5 °C otherwise. In this study, there is no active cooling system and we aim to optimize passive cooling solutions. A heat recovery ventilation (HRV) system provides 0.5 air changes per hour (ACH) during occupancy hours. Artificial lighting is turned off when natural daylighting exceeds 300 lux by using the daylight factor [32,33]. To improve building summer comfort, natural ventilation operates during nights from 23:00 p.m. to 06:00 a.m. by opening ad-hoc vents in the lower part of the building and skylights located on the roof.

3. Methodology

3.1. Passive strategies for low energy consumption and summer comfort

In order to improve the building thermal performance, some techniques of passive solutions were considered here (Table 3). They can be characterized according to various building aspects: geometry (orientation, surface of skylights), thermal insulation (ground, roof and vertical walls), and passive cooling techniques (reflective coating of roof surface, natural night ventilation).

3.1.1. Strategy of natural night ventilation

In the present study, the natural night ventilation (NNV) through

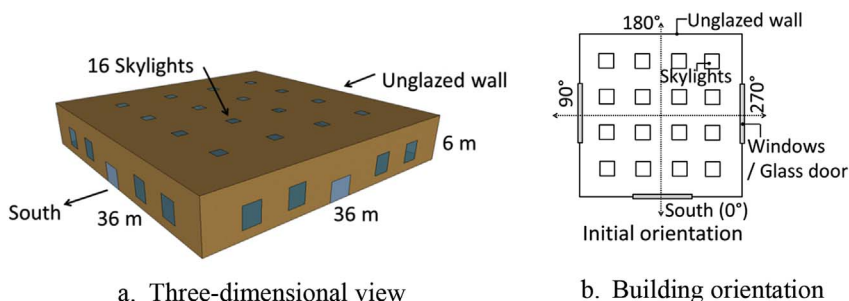


Fig. 1. Geometry of the studied low-rise commercial building.

Table 3
Optimization parameters and its impact on heating, cooling, lighting and ventilation systems.

Optimization parameters	Heating	Cooling	Lighting	Ventilation	Values	Unit
Building orientation	×	×	×		0–360	°
Solar reflectivity of roof	×	×			0,1–0,9	–
Skylights surface area	×	×	×	×	2,5–15	%
Roof thermal insulation	×	×			0,1–50	cm
Ground thermal insulation	×	×			0,1–50	cm
Vertical wall insulation	×	×			0,1–50	cm
Temp-setup for opening skylights	×	×		×	15–26	°C
Temp-setup for closing skylights	×	×		×	19–26	°C

skylights is controlled by indoor air temperature. Its goal is to keep the indoor temperature within the comfort range of 19–26 °C [34]. We introduce two different periods on the NNV strategy: (1) the authorization period of ventilation and (2) the ventilation period. The first one representing the summer period in which the NNV is highly recommended. This period is determined by the following equation:

$$NV_t = GT(T_{a,i}, T_{close}) + (LE(T_{a,i}, T_{open}) \cdot GT(T_{a,i}, T_{close})). NV_{t-1} \quad (1)$$

where NV_t and NV_{t-1} are the authorization signal of the NNV at the current time (t) and the previous time ($t-1$), $T_{a,i}$ is the indoor air temperature (°C), T_{close} and T_{open} are the temperature setup for opening (19 °C) and closing skylights (26 °C). LE (lower than) and GT (greater than) are comparative functions (1 or 0 values for respectively true or false results). Skylights remain closed during the $NV_t = 0$ period. Then, skylight opening is controlled by outdoor temperature and possible rainfall. To avoid overheating, skylights are closed when outdoor temperature is higher than indoor temperature. Considering rainfall through a simplified approach (this weather data was not available), skylights are closed when outdoor relative humidity is higher than 95%. Subsequently, the actual period of skylight opening (natural ventilation period) can be determined by the following expression:

$$Open = Night \cdot NV_t \cdot GT(T_{a,i}, T_{a,e}) \cdot GT(HR, HR_{cons}) \quad (2)$$

where $Open$ is the control signal of opening (1 = open, 0 = close), $Night$ is a Boolean variable, $Night = 1$ during the nighttime period (11:00 p.m.–06:00 a.m.), $T_{a,e}$ is the outdoor air temperature (°C), HR is the outdoor relative humidity (%), HR_{cons} is the maximal relative humidity (95%).

3.2. Building thermal simulation model

The simulation of the commercial low-rise building has been performed using the coupling between the TRNSYS[®] building model (Type 56) and the CONTAM[®] airflow model (Type 97) under the TRNSYS 17

simulation environment. As illustrated in Fig. 2, the building is modeled as a unique zone (nodal approach) that interacts with the following main elements: the *Airflow Model* to calculate the airflow rates through openings and the envelope, the *Roof Thermal Model* to account for cool roof radiative properties and the *Ground Thermal Model* to evaluate heat transfers through the ground.

As airflow rates of infiltration and natural ventilation are induced by wind and stack effects, wind pressure coefficients on the building envelope have to be provided. In this study, we used the Swami and Chandra correlations [35]. Moreover, heat transfer through the ground is modelled by a tridimensional approach described in our previous papers [36,37]. Each simulation is performed for a 2-years period, with a first year of initialization in order to have correct thermal values for the ground.

3.3. Optimization method

The optimization method aims to determine the non-dominated solution defined by the set of eight design parameters (presented in Table 3) to minimize building primary energy consumption for heating and lighting (EP [kWh/m²/yr]) and degree-hours of summer thermal discomfort (DH [°Ch]), see Eq. (3). The discomfort criteria DH is evaluated by adaptive comfort model [34]. We used a multiobjective genetic algorithm method based on the NSGA-II algorithm [24]. NSGA-II algorithm has been widely applied in building physics, such as optimization of building design [38], renovation of the existing building [39], optimization of energy consumption in nearly zero-energy buildings [40]. NSGA-II is mainly based on a non-dominated sorting and crowding distance sorting mechanisms. The NSGA-II input parameters include the population size, number of generations, mutation probability, crossover probability and number of objectives. The objective function is then defined by:

$$f_{obj}(x) = \min(EP(x), DH(x)) \quad (3)$$

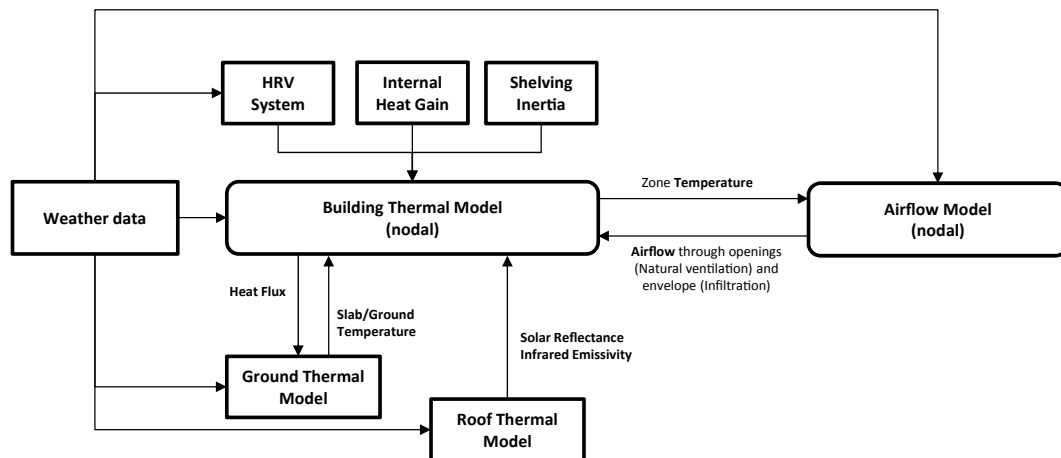


Fig. 2. Coupled models.

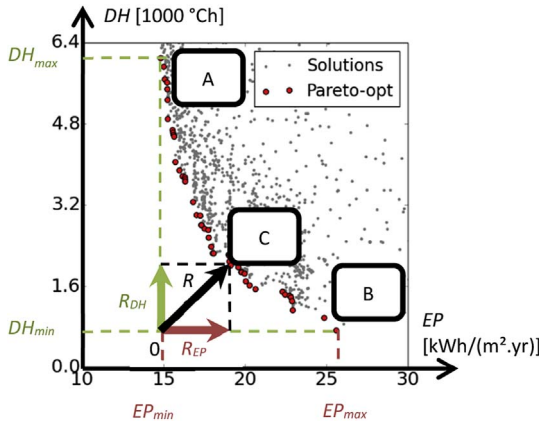


Fig. 3. Pareto optimal solutions and compromise solution (A, B, C).

3.3.1. Selection criteria for the optimal solutions

The choice of a Pareto optimal solution depends on the compromise between both objectives that can be normalized between minimum and maximum values through coefficients R_{EP} and R_{DH} as illustrated Fig. 3. The solution A is the most energy efficient solution (i.e. $R_{EP} = 0$) and has the highest summer discomfort (i.e. $R_{DH} = 1$). On the contrary, the solution B is the optimal solution to minimize summer discomfort (i.e. $R_{DH} = 0$) with the maximum energy consumption (i.e. $R_{EP} = 1$), and solution C is a trade-off between both objectives (Eq. (4)). This trade-off is defined by the weighting factors R_{EP} and R_{DH} (Eq. (5), Eq. (6)).

In the following study, our compromise solution is represented by a minimum value of $\bar{R}$ (Eq. (7)).

$$f(\vec{x})_C = R_{EP} \cdot EP(\vec{x}_{EP, R_{EP}}) + R_{DH} \cdot DH(\vec{x}_{DH, R_{DH}}) \quad (4)$$

$$R_{EP} = \frac{EP(\vec{x}_{EP, R_{EP}}) - EP_{min}}{EP_{max} - EP_{min}} \quad (5)$$

$$R_{DH} = \frac{DH(\vec{x}_{DH, R_{DH}}) - DH_{min}}{DH_{max} - DH_{min}} \quad (6)$$

$$\bar{R} = \sqrt{R_{EP}^2 + R_{DH}^2} \quad (7)$$

3.3.2. Additional criterion for optimal solution selection

The trade-off solution obtained previously is then re-evaluated by an additional criterion: the building construction cost. We seek the minimum construction cost around the selected trade-off solution, i.e. with similar energy and summer comfort performances. This preferred solution is obtained by minimizing the construction cost related to proposed passive solutions (R_C) and calculated by the following equation:

$$R_C = (C_P \cdot e_P \cdot S_P) + (C_T \cdot e_T \cdot (S_T - S_L)) + (C_M \cdot e_M \cdot S_M) + C_L \cdot S_L \quad (8)$$

R_C is the construction cost (€), C is the material and labor cost (€), e is insulation thickness (cm), S is the material surface (m^2) and indexes P , T , M , L for respectively “ground floor”, “roof”, “vertical walls” and “skylights”. Construction costs (including material and labor costs) are given in Table 4.

3.3.3. Preliminary study – convergence and optimization parameters

In a first stage, we studied the convergence rate according to the generation number of the NSGA-II algorithm. Better convergence toward actual optimal results can be obtained increasing generations, whereas we are limited by computation time. From the 9th generation, the convergence progress is attenuated with an absolute error of 3% compared to the next generation but the result diversification in the Pareto front is more intensive, as illustrated Fig. 4. The computation

Table 4

Construction cost for the passive solutions.
source 2015: <http://prix-construction.info/>.

Parameters	Price (€/unit)	Unit	Type/Remark
<i>Skylights</i>	1184	1,96 m ²	Single glazing, square 1.4 × 1.4 m ² , electric motor, rain and wind sensor
<i>Ground floor</i>			
Thermal insulation			
- 3 cm thickness	13,48	m ²	Extruded polystyrene
- 10 cm thickness	23,66	m ²	
<i>Roof and vertical walls</i>			
Non-insulated wall (fixed)	25	m ²	Galvanized steel wall
Steel wall with thermal insulation			
- 3 cm thickness	52,25	m ²	Rockwool insulation
- 12 cm thickness	66,52	m ²	

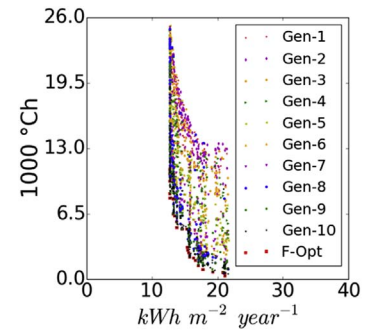


Fig. 4. Evolution of optimal solutions according to generation number.

time of simulations with an eight-processor PC is about 28 h, for an optimization of 200 individuals per generations and 10 generations. The obtained results with these optimization parameters converge with a reasonable accuracy.

Then, we set here an initial population of 200 individuals, 10 generations, a 0.9 crossover coefficient and a 0.04 mutation coefficient. These values can be comparable to earlier studies about optimization parameters [41–43].

3.4. Weather conditions

Three locations have been selected to represent different climatic regions (based on Köppen climate classification) tropical, Mediterranean and oceanic, see Table 5. Especially within the French region, we selected 24 additional locations to represent different climatic zones. These locations regularly distributed in the country cover correctly the eight climatic zones defined by building energy regulation. We have also investigated for each location the global warming effect on the optimal design parameters of buildings. The climate change weather data was determined for 2080 using a morphing method developed by University of Southampton [44,45]. This climate change simulation is a rough first approach to study the necessary modifications and consequences with a high-emission IPCC scenario. Current and 2080 meteorological data are summarized for the selected locations in Table 5.

4. Results and discussions

4.1. Mapping optimal solutions for France

4.1.1. Energy demand and summer comfort

In a first approach, we selected optimal solutions considering the trade-off between primary energy demand and thermal discomfort

Table 5
Meteorological data of different locations.

Parameters	Jakarta Indonesia	Marseille France	Poitiers France
Type of climate	Am-Tropical	Cd-Mediterranean	Cf-Oceanic
Latitude (°)	6.08 S	43.43 N	46.58 N
Longitude (°)	106.9 E	5.22 E	0.32 E
<i>Current conditions</i>			
Temperature (°C)	27.3	14.8	11.6
Relative humidity (%)	79.8	68.6	78.5
Mean/max – solar radiation (W.m ⁻²)	417/1053	353/986	289/930
Wind velocity (m.s ⁻¹)	2.15	4.87	3.89
Heating Degree-Hours base 19 °C (°Ch)	0	48 500	70 374
Cooling Degree-Hours base 26 °C (°Ch)	17 102	1217	382
<i>Year 2080</i>			
Temperature (°C)	30.1	18.7	15.7
Relative humidity (%)	79.0	63.5	70.2
Mean/max – solar radiation (W.m ⁻²)	431/1113	378/1102	314/1058
Wind velocity (m.s ⁻¹)	2.28	4.87	4.0
Heating Degree-Hours base 19 °C (°Ch)	0	31 138	47 194
Cooling Degree-Hours base 26 °C (°Ch)	36 586	8359	4870

obtained for the current and 2080 climate in France. These solutions are determined for each location (24 selected locations representing 8 French standard climatic zones) for the best compromise $\min(R_C)$, defined around the solution C (Fig. 3) considering construction costs ($\min \bar{R}_C$). In order to present a comprehensive mapping and analysis, the results are interpolated throughout French territory. The optimization process gives both the obtained performance for two criteria detailed here, and the corresponding design parameters presented in the following sections. The optimal building consumption for the current climate varies between 18.9 kWh/m²/yr (Nice, southeastern area) and 65.7 kWh/m²/yr (Metz, northeastern area) (Fig. 5a). In summer, the building configuration of the trade-off solution can ensure the

thermal comfort in almost all French regions, except in a little part of southern one where a small amount of discomfort is observed with a maximum value of DH of about 117 °Ch in Marseille (Mediterranean climate) (Fig. 5b).

With an average temperature increase of 3.9 °C across the country, the energy consumption in 2080 decreases slightly with an average reduction of 9 kWh/m²/yr and values varying between 21.2 and 50.9 kWh/m²/yr (Fig. 5c). We observed the greatest energy reduction (16.1 kWh/m²/yr) in Lille (northern part of France). Concerning the summer comfort, DH varies from 1.3 (Brest, northwestern area) to 1662 °Ch (Marseille). The average DH increase is about 265 °Ch due to global warming. Once again, we observed the most significant increase in Marseille with 1544 °Ch (13 times compared to the current climate).

4.1.2. Geometry aspects

4.1.2.1. Building orientation. An appropriate building orientation can provide significant passive solar heating without causing summer discomfort. In France, the observed optimal orientation varies between 77° (West) and –82° (East). Typically, the optimal orientation for the northern region is south (0°). For the southern region of France, the building should be oriented to southeast. For example, optimal orientations for Marseille, Nice, Perpignan and Socoa, are –70°, –79°, –82° and –78°, respectively (Fig. 6a). Considering 2080 climate, the optimal orientation is southwest or southeast (Fig. 6b).

4.1.2.2. Surface area of skylights. Significant solar heat gains and natural lighting transmitted by skylights can cover a significant part of the building energy demand. However, for a well-insulated building, skylights are the weakness point that represents a significant heat loss. For natural ventilation purpose, skylights' area is the main parameter to increase the magnitude of the natural airflow rate. The optimal surface area of skylights varies between 2.5 and 7.5% (Fig. 6c). Since the U-value of skylights is higher than that of the roof, the lowest skylights' area (< 4%) is considered as the optimal solution for the northern region. In addition, the daylighting in this area is not significant and has a low impact on artificial lighting use. In the southern region, the optimal skylights' area is about 7.5%. Natural lighting can cover a

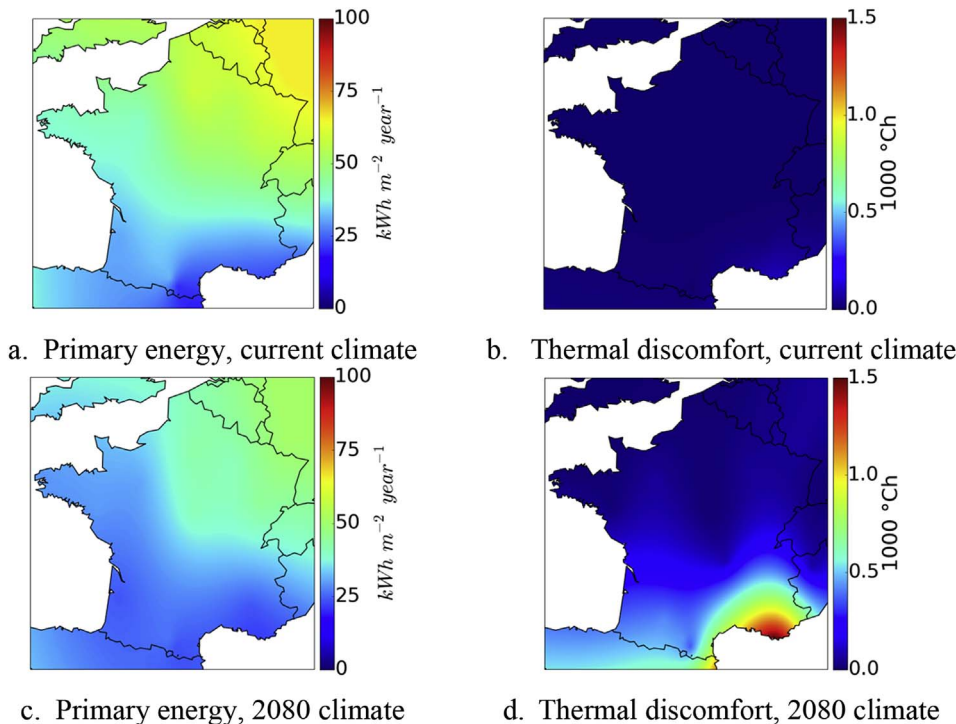
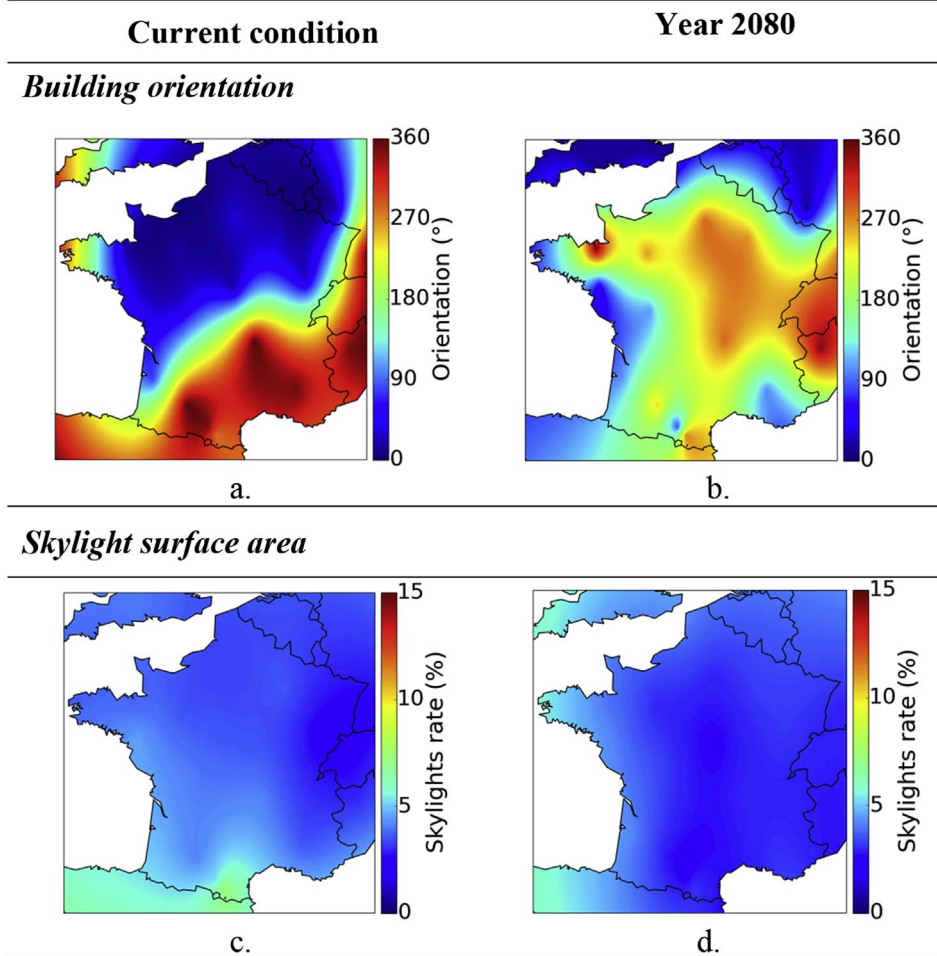


Fig. 5. French map of optimal solutions' results – energy demand (kWh/m²/yr) and thermal discomfort (°Ch), current and future climate.

Fig. 6. Optimal solution for building orientation and skylight surface area.



significant part of the lighting requirement. Natural ventilation can mitigate summer thermal discomfort caused by high solar heat gains.

In 2080, summer thermal discomfort raises, due to significant outdoor temperature increase of the southern region (e.g. 3.95 °C in Marseille). Large areas of skylights lead to a counterproductive impact on summer comfort. Moreover, natural ventilation efficiency in future climate decreases. The optimal skylights' area in the southern region is then around the minimum value, 4% (Fig. 6d). For the northern region, the optimal skylights' area varies less compared to the current climate, from 4 to 6% (Fig. 6d).

4.1.3. Thermal insulation

Increasing thermal insulation of the envelope (roof and vertical walls) is a passing solution for moderate-cold climate to reduce heating demand. In the current climatic conditions, the optimal thickness for the envelope is about 45–50 cm (Fig. 7a), except for a small part of the southern region where the vertical walls insulation thickness is found slightly lower (30–40 cm). For the ground floor, the optimal thickness of insulation varies a lot (0–47.5 cm). In the Mediterranean region, an uninsulated floor is preferred in order to benefit of the ground thermal inertia for the passive cooling. In these southern regions, optimal insulation thickness is intermediate (20 cm). For the other areas, the ground floor has higher insulation thickness (40 cm) in order to minimize winter thermal heat losses (Fig. 7a).

In 2080, the optimal roof insulation thickness for the northern regions decreases significantly from 50 cm to 25 cm. We observed a similar trend for the vertical walls, except for a small part of the northern region. We obtained a substantial decrease of floor insulation thickness for the whole country for the climate of 2080 (Fig. 7f).

4.1.4. Passive cooling strategies: cool roof and natural night ventilation

4.1.4.1. Implementation of cool roof. France is characterized by oceanic climates for the western part, Mediterranean climate for the southern part and continental climate for central and eastern regions. Winter heating demand has more impacts on the building design in the northern regions. In order to increase solar heat gains for winter period, the building envelope should have a low coefficient of solar reflectance (high absorption). The optimal value of albedo for the northern region is 0.2 (Fig. 8a). While in the southern region, indoor conditions during winter and summer are almost equally important. However, in this region, overheating in summer can be critical for this commercial building typology. To overcome this problem, the reflective coating on insulated roof is a straightforward solution. We found an optimal solar reflectance in the Mediterranean regions around 0.7 (Fig. 8a).

Considering global warming climate, we observed that cool roof should be implemented throughout French territory. This solution improves summer comfort of building without cooling system, except for a little part of the northern region (Fig. 8b). We observed optimal values of solar reflectance in 2080 from 0.8 to 0.9, except in the northern region (from 0.3 to 0.5).

4.1.4.2. Strategy of natural night ventilation (NNV). Depending on the climate, passive cooling effectiveness can be increased in summer with the NNV strategy. We observed that the NNV operation should be controlled by temperature set points of 18–26 °C both for the current climatic condition and the year 2080 (Fig. 8c–f).

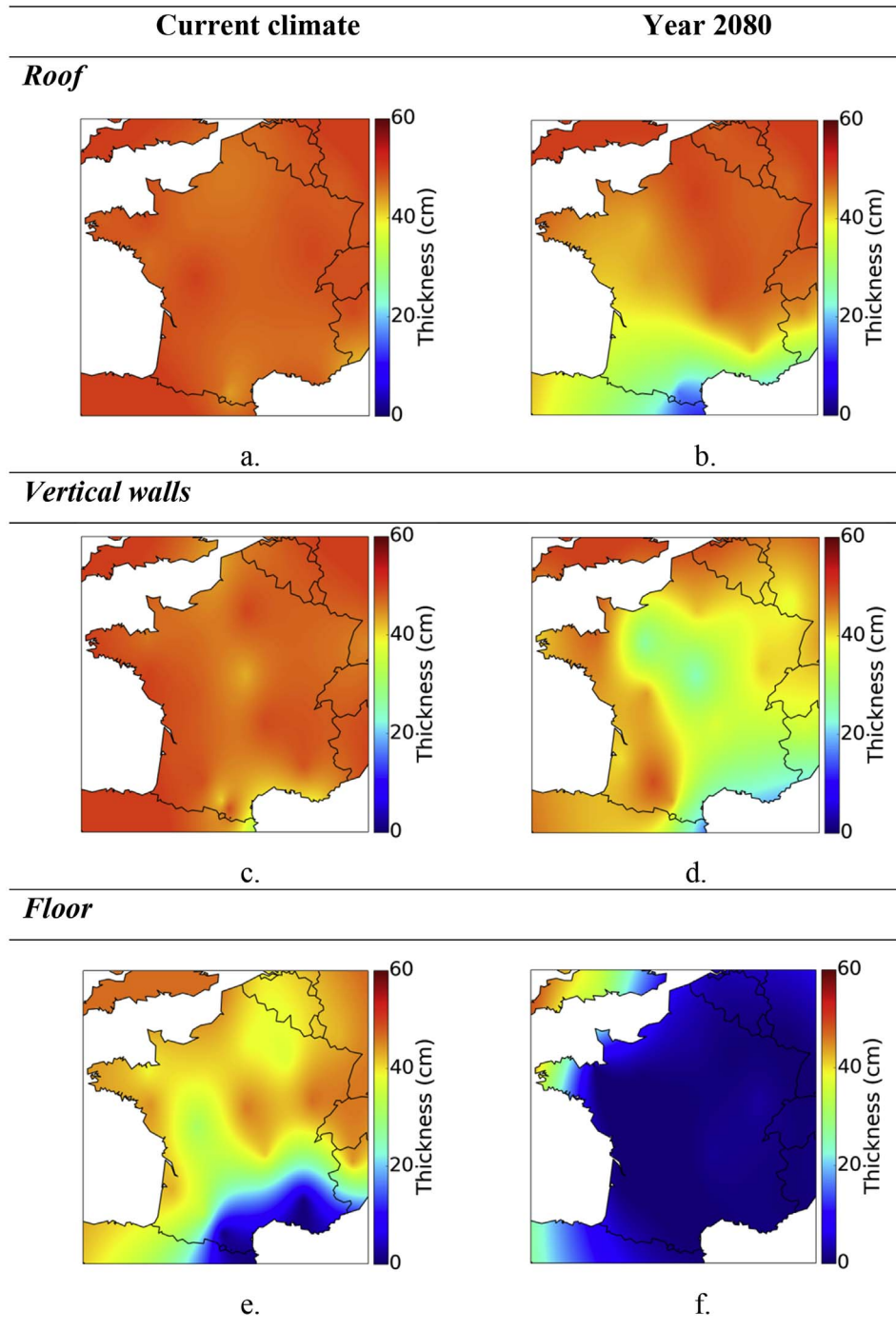


Fig. 7. Optimal solution for thermal insulation.

4.2. Optimal solutions for three climates – current and future

Pareto optimal results are presented Fig. 9 for each selected climatic region (cities of Jakarta, Marseille and Poitiers), and the three optimal solutions defined by the minimum values of R_{EP} , R_{DH} and R_C (see sections 3.3) are detailed Table 6 for current and 2080 climate.

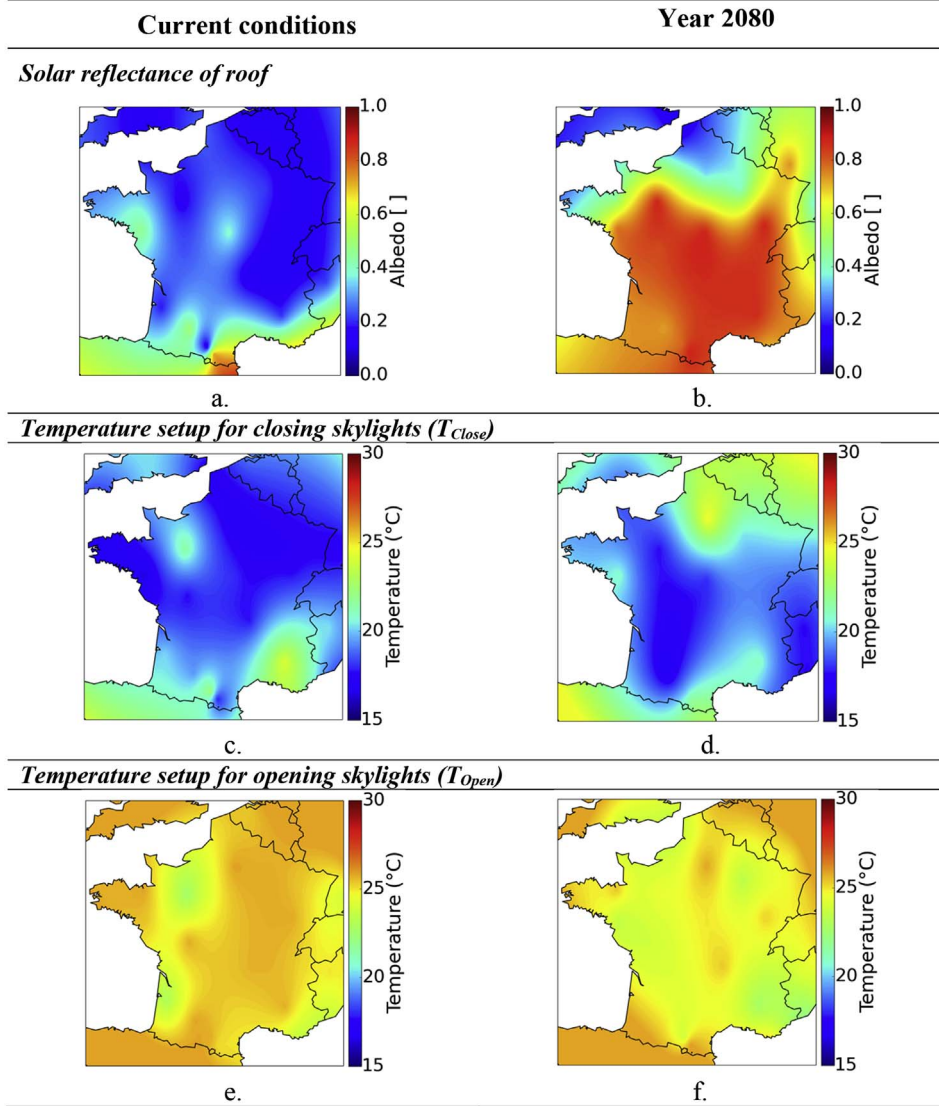
We observed strong differences between Pareto front solutions for each location, with a common visible effect of climate change on the increased thermal discomfort (DH). We analyzed the detailed variations of optimal solutions through their thermal performances (energy demand and summer thermal discomfort) and design parameter sets (summarized in Table 6) throughout the following sections.

4.2.1. Primary energy demand and thermal discomfort

Thermal discomfort due to overheat can be totally mitigated for various climates, and is minimized to 338 °C.h for the warmest one (tropical). For this tropical climate, as ambient temperature during occupancy period is always greater than the heating set point (19 °C), there is heating demand and the maximum energy efficiency is obtained by natural lighting with the maximum skylights' area. For the other two climates, oceanic and Mediterranean, winter heating demand and summer thermal comfort are balanced; the primary energy demand variations (EP) due to winter heating needs can be mitigated with passive envelope design for winter.

Compared to the 2080 climate, see Fig. 10, the same effect of thermal discomfort increase is observed for the three locations. In

Fig. 8. Optimal solutions for passive cooling strategy.



tropical climate, overheating degree-hours DH increase from 5156 to 12 831 °Ch (149%). On the contrary, primary energy needs (mainly due to heating needs) strongly decrease. But, for the Jakarta climate (energy demand only for artificial lighting) the results are not modified. In the oceanic climate, average temperature increases by 4.18 °C in 2080, and building energy consumption decreases by about 10.4 kWh/m²/yr (26.2%) compared to the current climate.

4.2.2. Solar reflectance of roofs

Low albedo values for roofs, from 0.16 to 0.30 (see Table 6), are obtained whenever the heating demand is the main concern (Mediterranean and oceanic climates). On the contrary, cool roof (albedo around 0.9) is a passive solution to mitigate summer overheating which is optimal for tropical climate, current and future Mediterranean climate, and oceanic future climate. Balanced values of solar reflectance were found to be optimal for oceanic and Mediterranean climates

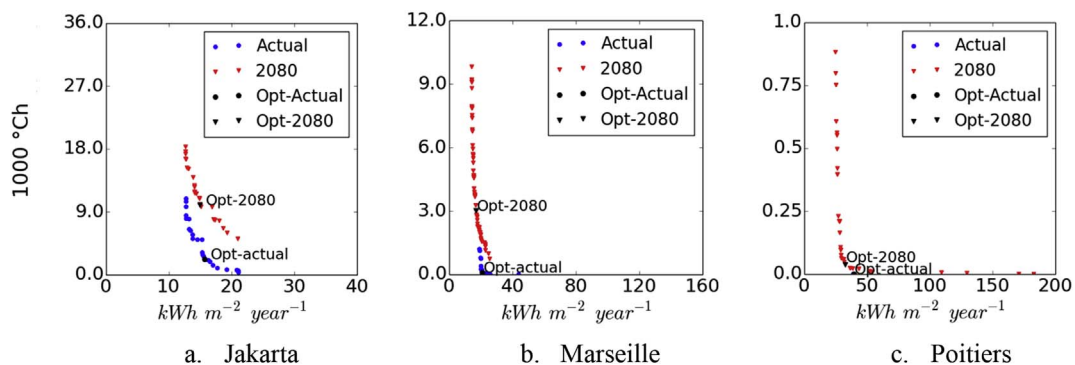


Fig. 9. Pareto front solutions for different climatic regions; current and 2080 climate.

Table 6
Parameter sets for three optimal solutions per location; current and 2080 climates.

	Objectives		Roof			Slab	Wall	Natural ventilation	
	R_{EP} kWh/m ² /yr	DH °Ch	Albedo	Skylight m ²	Insulation cm	Insulation cm	Insulation cm	T_{Close} °C	T_{Open} °C
Current climate									
Jakarta - Af Equatorial climate									
min R_{EP}	12.76	10 890	0.90	15.0	1.2	12.4	37.9	19.7	25.2
min R_C	13.82	5 156	0.90	10.9	0.7	1.4	2.2	16.0	21.0
min R_{DH}	21.11	338	0.88	2.7	0.5	2.0	14.7	16.0	20.6
Marseille - Cd Mediterranean climate									
min R_{EP}	19.14	1 192	0.16	9.2	46.1	0.7	48.8	19.5	25.6
min R_C	21.63	118	0.74	4.8	48.8	2.2	37.5	22.9	23.5
min R_{DH}	43.87	0	0.84	3.0	8.6	1.1	44.2	19.1	23.8
Poitiers - Cf Oceanic climate									
min R_{EP}	39.10	0.9	0.30	4.1	47.8	48.5	48.4	16.6	25.9
min R_C	39.75	0.3	0.23	4.0	49.9	31.1	48.2	17.6	25.8
min R_{DH}	40.00	0	0.32	4.4	49.9	30.6	49.6	17.6	25.8
future climate (2080)									
Jakarta - Modified equatorial climate									
min R_{EP}	12.68	18 302	0.88	15.0	0.9	17.2	3.6	15.7	25.9
min R_C	14.12	12 831	0.89	9.8	1.1	4.7	2.3	17.1	25.2
min R_{DH}	21.00	5 133	0.90	2.6	0.9	12.3	0.9	19.4	20.6
Marseille - Modified Mediterranean climate									
min R_{EP}	14.27	9 808	0.70	14.6	34.4	3.8	49.9	21.2	25.4
min R_C	21.24	1 662	0.69	3.3	18.3	1.4	18.1	18.9	25.6
min R_{DH}	25.60	731	0.89	2.7	8.0	0.8	40.2	22.7	25.2
Poitiers - Modified oceanic climate									
min R_{EP}	24.90	882	0.17	6.3	49.8	0.5	44.8	17.7	24.6
min R_C	29.40	111	0.46	3.4	43.7	0.6	43.8	17.6	24.0
min R_{DH}	32.70	37	0.82	2.8	47.3	0.5	47.0	18.4	21.2

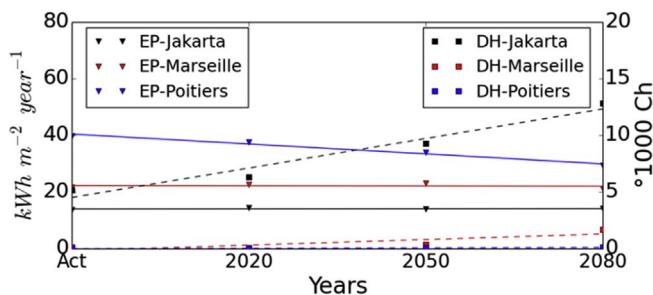


Fig. 10. Impact of global warming on energy demand EP and thermal discomfort DH.

(0.46–0.74) considering the trade-off solutions between energy demand and thermal discomfort.

The cool roof is an interesting solution for Jakarta that does not depend on R_{EP} value and is always beneficial for energy performance. For the current climate, we observed an optimal albedo from 0.8 to 0.9 (Fig. 11a). In Marseille, winter heating demand and summer thermal comfort problems are equally important. The implementation of cool roof causes conflicting consequences for the optimal solutions. For lower energy consumption ($R_{EP} = 0$), optimal solutions have a conventional dark roof (albedo from 0.1 to 0.3). Balanced solutions between summer thermal discomfort and energy demand (R_{EP} around 0.4), have an increased albedo (from 0.3 to 0.8). Otherwise, to ensure summer comfort, the roof surface should be covered by a reflective coating (albedo 0.9). In Poitiers, the conventional roof with a dark surface (albedo 0.1–0.3) is better to increase solar gains. However, it should be pointed out that we did not take into account the snow effect which could significantly changes the results, as demonstrated in other studies [21,46].

Considering the climate change, the cool roof is still interesting or even essential for Jakarta and Marseille. While for Poitiers, the optimal values of albedo increase from 0.23 to only 0.46.

4.2.3. Roof openings through skylights

In tropical climate, skylights' areas (see Table 6) are increased (15 m²) to minimize energy demand due to lighting. In Mediterranean climate, these surfaces are increased too in order to increase winter solar heat gains. However this has a negative impact on the summer thermal comfort, which explains low values (around 3 m²) when minimizing overheating in all considered climates.

Skylights have a significant impact on heating and lighting energy consumption, and summer comfort. Actually, their effects on building thermal and airflow behavior are quite complex. They provide passive solar gain and natural lighting (which covers a significant part of energy demand), they are also key elements for natural night ventilation, but they increase thermal losses in winter.

Fig. 12 shows the nonlinear impact of the skylights' area according to the R_{EP} coefficient. The optimal surface area in Jakarta is about the same for current and 2080 climates. To achieve a low-lighting energy demand, the surface area should be as large as possible, up to 15% here (Fig. 12a). However, to ensure thermal comfort, optimal skylights' area is found to be reduced as much as possible (2.5%). In Marseille, the optimal area for summer comfort ($R_{EP} = 0$) is 8.75%. Taking into account both energy consumption and summer comfort, this area should be kept between 10 and 11%, 3–5% and 4–5%, for respectively Jakarta, Marseille and Poitiers.

4.2.4. Thermal insulation thickness

We observed (see Table 6) that wall insulation (and especially roof insulation) is not required for summer comfort concerns, i.e. tropical

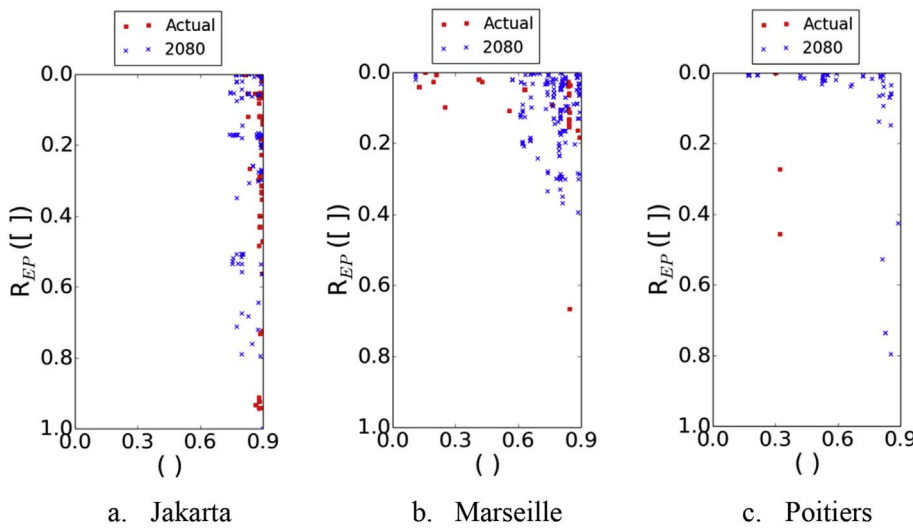


Fig. 11. Optimal values of roof solar reflectance.

climate and Mediterranean climate for low R_{EP} values. Considering temperate climates and minimum heating demand (Oceanic and Mediterranean climates), we found an increased insulation thickness to the maximum value for roof and vertical walls. However, in order to benefit from the thermal inertia of the ground, the slab insulation is generally not obtained as an optimal solution except for the cold oceanic climate where the overheating can be managed with night ventilation and low inertia for this building typology.

Increased insulation thickness reduces heat transfer through building envelope and limits indoor temperature changes. For large volume and low-rise buildings (large ground floor and roof areas), the thermal insulation on these two components is a critical factor. Depending on the R_{EP} variation (trade-off between summer thermal comfort and energy demand), optimal values of thermal insulation thicknesses varies more or less (see Fig. 13).

4.2.4.1. Roof. At roof level, there are coupled effects between thermal insulation, thermal inertia of materials and radiative properties of the outside surface. For buildings with low heat gains in temperate regions (Marseille), higher thermal insulation of roof provides significant energy savings in winter. The best building energy performance is obtained with a thick thermal insulation (40–50 cm). Summer comfort is yet improved with a reduced thickness that is found to be optimal under 10 cm. We observed that optimal insulation thickness varies inversely to the optimal roof albedo. In Poitiers, the optimal insulation

thickness is maximum (50 cm) with no summer thermal discomfort.

Opposite results are obtained for the tropical region. There are higher heat gains (solar radiation, occupancy and lighting), and the roof insulation works against possible heat losses during night. The roof insulation is then not found optimal for current and future climate (Fig. 13a). However, this low-insulated roof increase solar heat gain, but this is well balanced by the cool roof solution.

4.2.4.2. Ground floor. In summer, computed ground temperature is usually cooler than indoor temperature during daytime. Hence, the ground floor can act as a heat sink for passive cooling. However, in winter, this can be also a significant heat loss. In Jakarta, ground temperatures remained constant and around the mean annual outdoor temperature (27.2 °C). Then, the ground thermal inertia potential revealed to be less important compared to the other studied regions (Fig. 13d). The optimal thickness in Poitiers for the current climate is about 25–30 cm (Fig. 13f). Due to global warming, this thickness would need to be decreased progressively. In Marseille, the optimal thickness is about 5 cm for the current climate and 2080 (Fig. 13e).

4.2.4.3. Vertical walls. In Jakarta, beam solar radiation affects mainly the building roof. Hence, for vertical walls, solar gains and insulation thickness are less significant (Fig. 13g). In Marseille and Poitiers climates, wall insulation has a real impact on the building thermal performance. The optimum insulation thickness is about 40–50 cm for

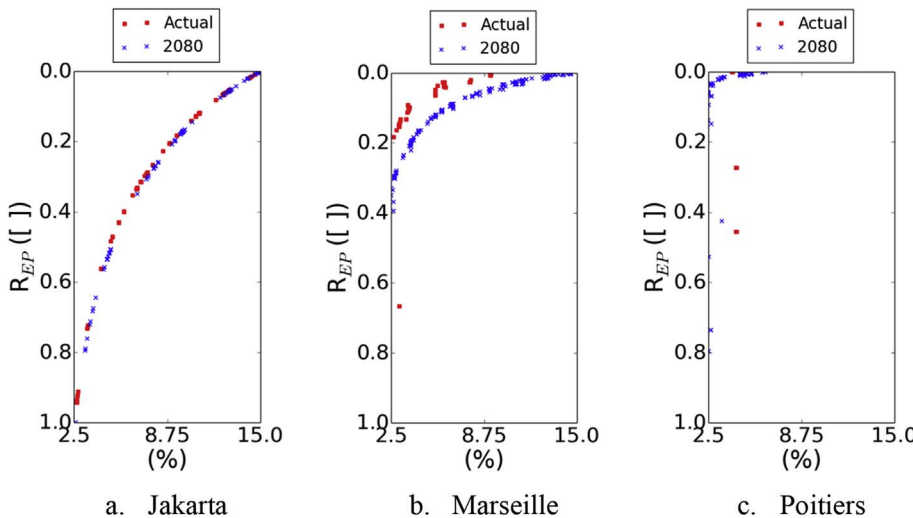


Fig. 12. Surface area of skylights.

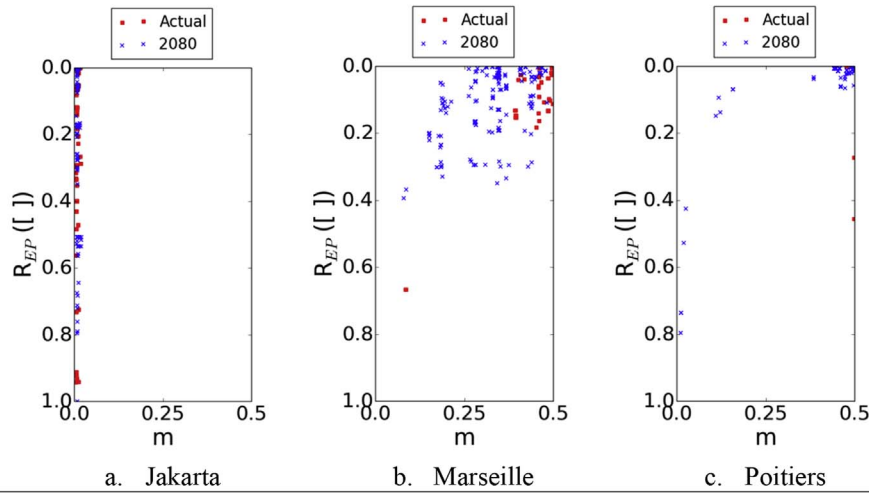
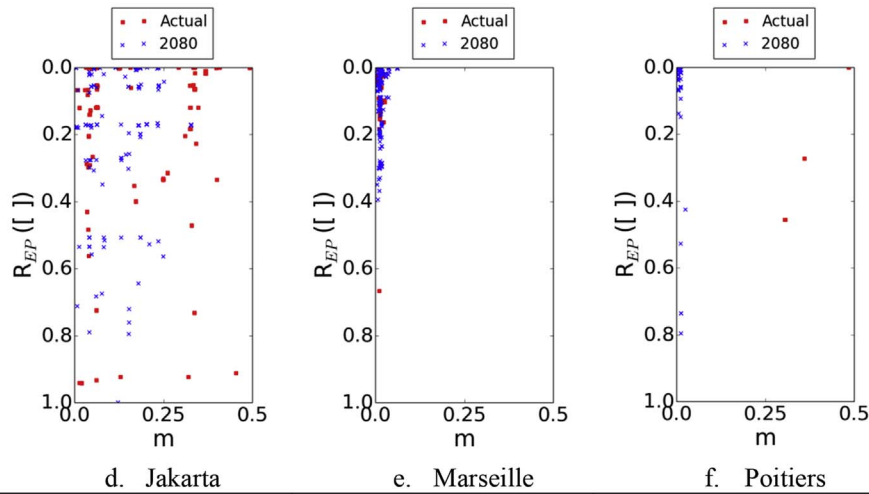
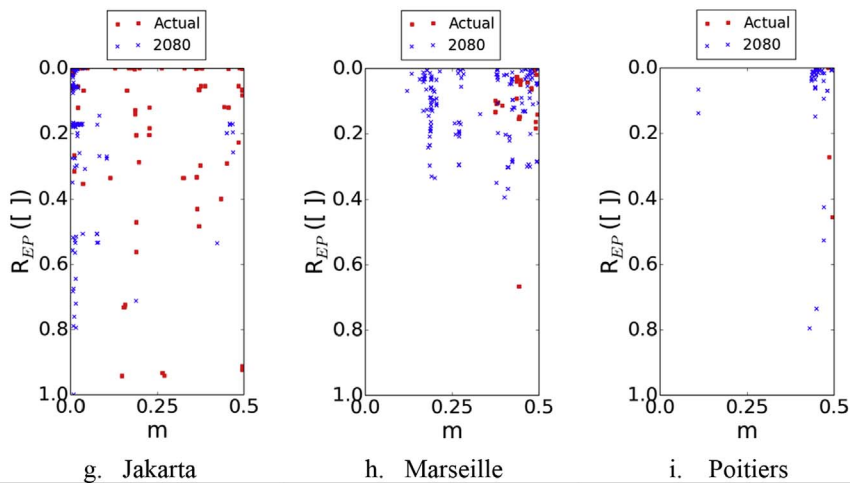
Roof thermal insulation thickness**Ground floor thermal insulation thickness****Vertical walls thermal insulation thickness**

Fig. 13. Impact of thermal insulation thickness (m) for roof, ground floor, and vertical walls; considering energy demand and summer comfort.

the current weather conditions. Global warming induces smaller thickness: 44 cm for Poitiers and 20–38 cm for Marseille (Fig. 13e).

4.2.5. Temperature setup for NNV strategy (opening and closing skylights)

NNV strategy participates to mitigate summer overheating without

penalizing heating consumption. The optimal temperature set points for the skylights' control varies according to the local climate (Fig. 14).

Increasing or decreasing temperature limits (to close or open skylights) affects in a contradictory way the heat gain conservation and the cooling potential of NNV. In Jakarta, for current and future climate,

Opening skylights

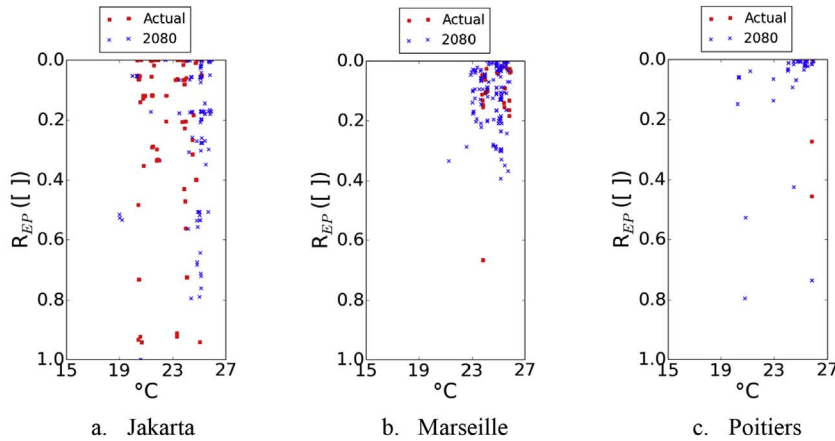
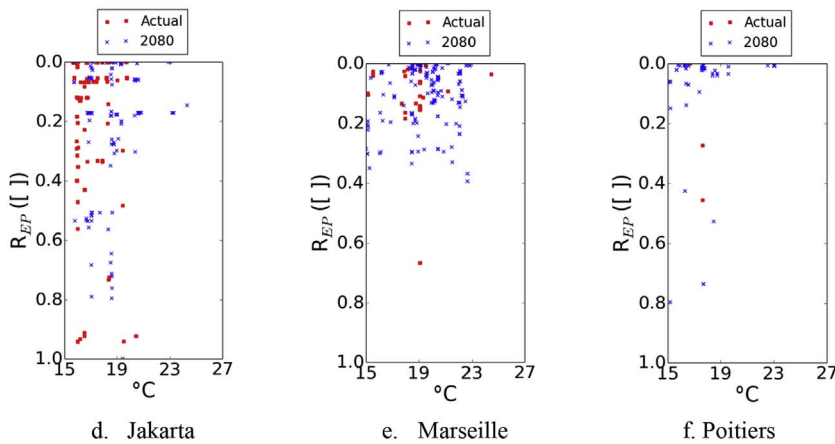


Fig. 14. Temperature setup for opening and closing skylights.

Closing skylights



NNV can operate for indoor temperatures from 20 to 24 °C (Fig. 14a). The minimum temperature to maintain skylights closed is often around the minimum value (16 °C) as heating demand is not a constraint (Fig. 14d). For the temperate and cold regions, the skylights should stay closed with a higher temperature setup (from 19 to 22 °C) to prevent heating overconsumption (Fig. 14e and f). With global warming effects (year 2080), this temperature set point for closing skylights decreases in Marseille and Poitiers.

5. Conclusions

The multicriteria optimization of building thermal performance by the NSGA-II algorithm used in the present study can serve as a decision support for the identification of effective strategies for energy retrofiting. We have presented the optimal solutions of passive strategies based on user's preferences for different climatic conditions. Three optimal solutions have been proposed: (1) the lowest energy consumption for heating and artificial lighting, (2) the most comfortable temperature in summer for the building without air conditioning and (3) the trade-off solution by taking into account the construction cost aspect on the compromise solutions of the two previous criteria. We considered also the global warming effect to determine the optimal solutions in the future climate 2080.

We identified the design parameter sensitivity and their impacts on passive techniques (building orientation, solar reflectance of roof, surface area of skylights, thermal insulation of the building envelope and set point temperature for the control of natural night ventilation) for overall building thermal performances. These optimization results

highlight the complex interaction between design parameters to obtain an optimal design, according to either summer thermal comfort or energy performance and based on geographical location.

Optimal set of parameters were mapped for France. These maps required intensive computing time but can be further used as design guidelines for decision makers and designers according to the geographical location for current climatic conditions and further climate change possible impacts. For the northern regions (France), the optimal solution have well-insulated envelope, small skylights' area, and standard roof with high solar absorption. For the southern regions, the optimal solutions have non-insulated ground slab, reflective cool roof and to large skylights' area to maximize night natural cooling potential and natural lighting.

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References

- [1] L. Pérez-Lombard, J. Ortiz, C. Pout, A review on buildings energy consumption information, *Energy Build.* 40 (2008) 394–398, <http://dx.doi.org/10.1016/j.enbuild.2007.03.007>.
- [2] M.M. Carvalho, E. La Rovere, A.C. Gonçalves, Analysis of variables that influence electric energy consumption in commercial buildings in Brazil, *Renew. Sustain. Energy Rev.* 14 (2010) 3199–3205, <http://dx.doi.org/10.1016/j.rser.2010.07.009>.
- [3] S. Charattananon, B. Limmeechokchai, A new building energy efficiency law in Thailand: impact on new building, *Energy* 19 (1994) 269–274.

- [4] M. Santamouris, Cooling the buildings – past, present and future, *Energy Build.* 128 (2016) 617–638, <http://dx.doi.org/10.1016/j.enbuild.2016.07.034>.
- [5] C. Piselli, M. Saffari, A. de Gracia, A.L. Pisello, F. Cotana, L.F. Cabeza, Optimization of roof solar reflectance under different climate conditions, occupancy, building configuration and energy systems, *Energy Build.* 151 (2017) 81–97, <http://dx.doi.org/10.1016/j.enbuild.2017.06.045>.
- [6] D.D. Kolokotsa, Office buildings/commercial buildings: trends and perspectives, *Energy Performance of Buildings*, Springer, Cham, 2016, pp. 203–216, http://dx.doi.org/10.1007/978-3-319-20831-2_10.
- [7] G. Caruso, J.H. Kämpf, Building shape optimisation to reduce air-conditioning needs using constrained evolutionary algorithms, *Sol. Energy* 118 (2015) 186–196, <http://dx.doi.org/10.1016/j.solener.2015.04.046>.
- [8] A.R. Gentle, J.L.C. Aguilar, G.B. Smith, Optimized cool roofs: integrating albedo and thermal emittance with R-value, *Sol. Energy Mater. Sol. Cells* 95 (2011) 3207–3215, <http://dx.doi.org/10.1016/j.solmat.2011.07.018>.
- [9] Y.K. Yi, H. Kim, Agent-based geometry optimization with Genetic Algorithm (GA) for tall apartment's solar right, *Sol. Energy* 113 (2015) 236–250, <http://dx.doi.org/10.1016/j.solener.2014.11.007>.
- [10] L.C. Ng, N.O. Quiles, W.S. Dols, S.J. Emmerich, Weather correlations to calculate infiltration rates for US commercial building energy models, *Build. Environ.* 127 (2018) 47–57.
- [11] J. Huang, H. Lv, T. Gao, W. Feng, Y. Chen, T. Zhou, Thermal properties optimization of envelope in energy-saving renovation of existing public buildings, *Energy Build.* 75 (2014) 504–510, <http://dx.doi.org/10.1016/j.enbuild.2014.02.040>.
- [12] Z. Romani, A. Draoui, F. Allard, Metamodeling the heating and cooling energy needs and simultaneous building envelope optimization for low energy building design in Morocco, *Energy Build.* 102 (2015) 139–148, <http://dx.doi.org/10.1016/j.enbuild.2015.04.014>.
- [13] A. Kusiak, M. Li, F. Tang, Modeling and optimization of HVAC energy consumption, *Appl. Energy* 87 (2010) 3092–3102, <http://dx.doi.org/10.1016/j.apenergy.2010.04.008>.
- [14] X. Wei, A. Kusiak, M. Li, F. Tang, Y. Zeng, Multi-objective optimization of the HVAC (heating, ventilation, and air conditioning) system performance, *Energy* 83 (2015) 294–306, <http://dx.doi.org/10.1016/j.energy.2015.02.024>.
- [15] H. Wang, Q. Chen, Impact of climate change heating and cooling energy use in buildings in the United States, *Energy Build.* 82 (2014) 428–436, <http://dx.doi.org/10.1016/j.enbuild.2014.07.034>.
- [16] D. Daly, P. Cooper, Z. Ma, Implications of global warming for commercial building retrofitting in Australian cities, *Build. Environ.* 74 (2014) 86–95.
- [17] D.H. Rosenthal, H.K. Gruenspecht, E.A. Moran, Effects of global warming on energy use for space heating and cooling in the United States, *Energy J.* 16 (1995) 77–96.
- [18] M. Olonscheck, A. Holsten, J.P. Kropp, Heating and cooling energy demand and related emissions of the German residential building stock under climate change, *Energy Pol.* 39 (2011) 4795–4806.
- [19] T. Frank, Climate change impacts on building heating and cooling energy demand in Switzerland, *Energy Build.* 37 (2005) 1175–1185.
- [20] A.L. Pisello, C. Piselli, F. Cotana, Influence of human behavior on cool roof effect for summer cooling, *Build. Environ.* 88 (2015) 116–128, <http://dx.doi.org/10.1016/j.buildenv.2014.09.025>.
- [21] M. Hosseini, H. Akbari, Effect of cool roofs on commercial buildings energy use in cold climates, *Energy Build.* 114 (2016) 143–155, <http://dx.doi.org/10.1016/j.enbuild.2015.05.050>.
- [22] A. Synnefa, M. Santamouris, H. Akbari, Estimating the effect of using cool coatings on energy loads and thermal comfort in residential buildings in various climatic conditions, *Energy Build.* 39 (2007) 1167–1174, <http://dx.doi.org/10.1016/j.enbuild.2007.01.004>.
- [23] M. Zinzi, S. Agnoli, Cool and green roofs. An energy and comfort comparison between passive cooling and mitigation urban heat island techniques for residential buildings in the Mediterranean region, *Energy Build.* 55 (2012) 66–76, <http://dx.doi.org/10.1016/j.enbuild.2011.09.024>.
- [24] K. Deb, A. Pratap, S. Agarwal, T. Meyarivan, A fast and elitist multiobjective genetic algorithm: NSGA-II, *IEEE Trans. Evol. Comput.* 6 (2002) 182–197, <http://dx.doi.org/10.1109/4235.996017>.
- [25] D.B. Belzer, M.J. Scott, R.D. Sands, Climate change impacts on US commercial building energy consumption: an analysis using sample survey data, *Energy Sources* 18 (1996) 177–201.
- [26] T. Denes, E. Bozonnet, I. Calmet, Modeling the global warming effect on indoor temperature peaks and cooling systems consumption, *Building Simulation 2009*, Glasgow, Scotland, 2009, p. 117 http://ibpsa.org/proceedings/BS2009/BS09_0117_122.pdf, Accessed date: 30 May 2010.
- [27] M. Karimpour, M. Belusko, K. Xing, J. Boland, F. Bruno, Impact of climate change on the design of energy efficient residential building envelopes, *Energy Build.* 87 (2015) 142–154, <http://dx.doi.org/10.1016/j.enbuild.2014.10.064>.
- [28] D. Barnard, Light Steel Construction and Modular Homes as Alternative Building Methods in South Africa, (2011) <http://www.repository.up.ac.za/handle/2263/16292>, Accessed date: 29 September 2015.
- [29] A.A. Zende, A.V. Kulkarni, A. Hutagi, Comparative study of analysis and design of pre-engineered-buildings and conventional frames, *IOSR J. Mech. Civ. Eng.* 2278–1684(2013).
- [30] A.K. Persily, Airtightness of Commercial and Institutional Buildings: Blowing Holes in the Myth of Tight Buildings, Building and Fire Research Laboratory, National Institute of Standards and Technology, 1998.
- [31] M. Deru, K. Filed, D. Studer, B. Kyle, B. Griffith, P. Torcellini, U.S. Department of Energy Commercial Reference Building Models of the National Building Stock, National Renewable Energy Laboratory, Colorado, US, 2011.
- [32] NF EN 12464-1, Lighting of Work Places, (2011).
- [33] M.S. Rea, Lighting Handbook: Reference & Application, eighth ed., Illuminating Engineering Society of North America, New York, 1993, p. 355.
- [34] NF EN 15251, Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics, (2007).
- [35] M.V. Swami, S. Chandra, Correlations for pressure distribution on buildings and calculation of natural-ventilation airflow, *ASHRAE Trans.* 94 (1988) 243–266.
- [36] R. Lapisa, E. Bozonnet, M. Abadie, P. Salagnac, R. Perrin, Effect of ground thermal inertia on the energy balance of commercial low-rise buildings, *Building Simulation 2013*, Chambéry, France, 2013.
- [37] R. Lapisa, E. Bozonnet, M.O. Abadie, P. Salagnac, Cool roof and ventilation efficiency as passive cooling strategies for commercial low-rise buildings – ground thermal inertia impact, *Adv. Build. Energy Res.* 7 (2013) 192–208, <http://dx.doi.org/10.1080/17512549.2013.865559>.
- [38] L. Magnier, F. Haghighat, Multiobjective optimization of building design using TRNSYS simulations, genetic algorithm, and Artificial Neural Network, *Build. Environ.* 45 (2010) 739–746, <http://dx.doi.org/10.1016/j.buildenv.2009.08.016>.
- [39] F.P. Chantrelle, H. Lahmidi, W. Keilholz, M.E. Mankibi, P. Michel, Development of a multicriteria tool for optimizing the renovation of buildings, *Appl. Energy* 88 (2011) 1386–1394, <http://dx.doi.org/10.1016/j.apenergy.2010.10.002>.
- [40] S. Carlucci, G. Cattarin, F. Causone, L. Pagliano, Multi-objective optimization of a nearly zero-energy building based on thermal and visual discomfort minimization using a non-dominated sorting genetic algorithm (NSGA-II), *Energy Build.* (2015), <http://dx.doi.org/10.1016/j.enbuild.2015.06.064>.
- [41] J.A. Wright, H.A. Loosemore, R. Farmani, Optimization of building thermal design and control by multi-criterion genetic algorithm, *Energy Build.* 34 (2002) 959–972, [http://dx.doi.org/10.1016/S0378-7788\(02\)00071-3](http://dx.doi.org/10.1016/S0378-7788(02)00071-3).
- [42] N. Nassif, S. Kaji, R. Sabourin, Optimization of HVAC control system strategy using two-objective genetic algorithm, *HVAC R Res.* 11 (2005) 459–486.
- [43] L. Gosselin, M. Tye-Gingras, F. Mathieu-Potvin, Review of utilization of genetic algorithms in heat transfer problems, *Int. J. Heat Mass Tran.* 52 (2009) 2169–2188, <http://dx.doi.org/10.1016/j.ijheatmasstransfer.2008.11.015>.
- [44] S.E. Belcher, J.N. Hacker, D.S. Powell, Constructing design weather data for future climates, *Build. Serv. Eng. Technol.* 26 (2005) 49–61.
- [45] M.F. Jentsch, P.A.B. James, L. Bourikas, A.S. Bahaj, Transforming existing weather data for worldwide locations to enable energy and building performance simulation under future climates, *Renew. Energy* 55 (2013) 514–524, <http://dx.doi.org/10.1016/j.renene.2012.12.049>.
- [46] M. Hosseini, H. Akbari, Heating energy penalties of cool roofs: the effect of snow accumulation on roofs, *Adv. Build. Energy Res.* 8 (2014) 1–13.